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RESISTIVE MAGNETIC FIELD GENERATION AT COSMIC DAWN

Francesco Miniati
Physics Department, Wolfgang-Pauli-Strasse 27, ETH-Zürich, CH-8093, Zürich, Switzerland; fm@phys.ethz.ch

A. R. Bell
Clarendon Laboratory, University of Oxford, Parks Road, Oxford UK OX1 3PU; t.bell1@physics.ox.ac.uk

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ABSTRACT

Relativistic charged particles (CR for cosmic-rays) produced by Supernova explosion of the first generation of massive stars that are responsible for the re-ionization of the universe escape into the intergalactic medium, carrying an electric current. Charge imbalance and induction give rise to a return current, $\vec{j}_t$, carried by the cold thermal plasma which tends to cancel the CR current. The electric field, $\vec{E} = \eta\vec{j}_t$, required to draw the collisional return current opposes the outflow of low energy cosmic rays and ohmically heats the cold plasma. Owing to inhomogeneities in the resistivity, $\eta(T)$, caused by structure in the temperature, T, of the intergalactic plasma, the electric field possesses a rotational component which sustains Faraday's induction. It is found that magnetic field is robustly generated throughout intergalactic space at rate of $10^{-17} - 10^{-16}$ Gauss/Gyr, until the temperature of the intergalactic medium is raised by cosmic reionization. The magnetic field may seed the subsequent growth of magnetic fields in the intergalactic environment.

Subject headings: plasma — large-scale structure of universe — magnetic fields:theory

1. INTRODUCTION

Massive stars characterized by high emission of ionizing UV photons are the main contributors to the process of cosmic re-ionization (e.g., Ciardi & Ferrara 2005). At the end of their life they explode as Supernovae accelerating, large amounts of CR protons (Krymsky 1977; Axford et al. 1977; Bell 1978; Blandford & Ostriker 1978). Since dynamo generation of magnetic fields operates very quickly within stars (Rees 2006), stars can magnetize their surroundings through their own magnetized stellar winds. Diffusive shock acceleration around Supernovae can, therefore, take place even without a pre-existing galactic magnetic field. Owing to their much higher energy and diffusive mean free path compared to thermal particles, CRs eventually escape from the parent galaxy into the intergalactic medium. Their escape may or may not be collimated by the galaxy disk (e.g. by the magnetic field in the wind around stars or a pre-existing galactic field if it exists). In any case, the CR protons carry a small but important electric current $\vec{j}_c$ which couples them to the thermal intergalactic medium and induce magnetic fields generation there. The phenomena described in this paper depend on the electrical current carried by the CR. Most of the current is carried at GeV energies, so our discussion does not depend upon CR acceleration to TeV or PeV energies. Also we neglect CR electrons as they are typically two orders of magnitude less numerous than protons (Schlickeiser 2002).

The Larmor radius of a proton of momentum p in a magnetic field B is $r_g = (p/mc)(B/10^{-15}G)^{-1}$kpc. In our discussion we will consider fields up to 10^{-16}G and protons energies up to 1GeV, so magnetic field will place very little restriction on intergalactic CR propagation. Even a spatial diffusivity unrealistically as small as the Bohm diffusivity, in which the mean free path is set equal to the Larmor radius, would allow GeV protons to diffuse a several Mpc in a 10^{-15} Gauss field after 1 Gyr. Interparticle collisions also place no restriction on propagation since the Coulomb collision time for GeV protons in a characteristic plasma density $\sim 10^{-4}\mathrm{cm}^{-3}$ is $\sim 10^3$Gyr. CR propagation within galaxies is not necessarily as clear cut since it is possible that the magnetic field, although largely unknown, may conceivably be much larger than in the intergalactic medium as result of processes associated with stars and supernovae. However, CR appear to diffuse freely around our own galaxy with present magnetic fields in the μG range. Even at energies in the GeV range, the presumption is that the galactic CR spectrum is determined by a balance between CR production by SNR and escape from the galaxy (Hillas 2005). Moreover, there is relatively direct evidence that even in the large magnetic field close to the center of our galaxy CR diffusion, far exceeding Bohm diffusion, is relatively free (Dimitrakoudis et al. 2009). Hence we base our discussion on the assumption that CR produced by early supernovae escape freely from their host galaxy. Once GeV protons escape into the intergalactic medium their propagation is restricted by neither collisions nor magnetic field.

In this paper we show that the electric currents carried by CRs protons produced in the first generation of galaxies that are also responsible for re-ionization of the universe is sufficiently large to generate significant magnetic fields throughout intergalactic space. The magnetic field is generated by the curl of the electric field associated with the return currents induced by the CR particle propagation. This process operates most efficiently while the intergalactic medium is cold, and effectively shuts down once reionization raises the intergalactic gas temperature above 10^4 K, i.e. when the universe was

about 1 Gyr old (Ciardi & Ferrara 2005). The generated magnetic field is typically of order 10^{-17}G at the end of reionization. This magnetic field may eventually be further enhanced by a turbulent dynamo (Ryu et al. 2008), although CR currents may play a further role in magnetic field amplification through Lorentz's force (Bell 2004, 2005).

Magnetic fields are observed in most astrophysical bodies from planetary scales, to stars and galaxies, and up to the largest structures in the universe (Zel'dovich et al. 1983; Kulsrud & Zweibel 2008). Nearby galaxies have been known to be magnetized for some time, but recent studies show that they acquire their fields when the universe was less than half its present age (Bernet et al. 2008; Kronberg et al. 2008). Since the growth of large scale magnetic field in a dynamo model is exponential in time, this poses serious restrictions on the timescale on which galactic-dynamo must operate.

Evidence for intergalactic magnetic fields is provided by Faraday rotation measure and diffuse synchrotron radiation which reveal the existence of μG strong magnetic fields in the hot plasma of galaxy clusters (Clarke et al. 2001; Carilli & Taylor 2002). These probes are considerably less sensitive to fields in adjacent structures such as small groups and filaments of galaxies. Nevertheless, these fields are expected to be there and large efforts are being made in an attempt to measure them. In addition, intergalactic magnetic fields affect the propagation of ultra high energy cosmic ray particles, introducing potentially measurable effects on their energy spectrum, arrival direction and composition (Sigl et al. 2004; Dolag et al. 2005; Hooper & Taylor 2010). Finally, the presence of magnetic fields in voids can affect the observed spectrum of extragalactic TeV γ-ray sources. Multi-TeV photons are absorbed by the diffuse extragalactic background light and converted into $e^{\pm}$ pairs which emit secondary cascade multi-GeV γ-rays by inverse Compton on the cosmic microwave background. The observed flux of pair produced GeV photons can be suppressed if the pairs are deflected from the line of sight by a magnetic field within an energy loss distance (Aharonian et al. 1994; Neronov & Semikoz 2009). Based on these ideas, in very recent studies[1] the γ-ray spectra of blazars were used to set lower limits to the value of magnetic fields in voids in the range $5 \times 10^{-15} - 5 \times 10^{-17}$G (Neronov & Vovk 2010; Tavecchio et al. 2010).

The presence of magnetic fields in astrophysical plasma requires a mechanism for their generation because, given the high mobility of the charges, sustained electrostatic fields are non-trivial to set up. However, even a weak seed may suffice because magnetic field amplification can occur at the expense of the plasma motions through the induced electric field, $\vec{E} = -\vec{v} \times \vec{B}$. Specific lower limits on the required seed strength depend on the astrophysical systems.

There already exist various scenarios for the generation of magnetic fields each with its strengths and weaknesses, among others Weibel's instability at shocks (Medvedev et al. 2006; Schlickeiser & Shukla 2003; Medvedev 2007); battery effects, e.g. due to Compton drag (Harrison 1970; Ichiki et al. 2006) or Biermann's mechanism either at cosmic shocks or ionization fronts (Subramanian et al. 1994; Kulsrud et al. 1997; Gnedin et al. 2000); galactic winds (Bertone et al. 2006; Donnert et al. 2009), processes in the early universe (Widrow 2002). In fact, the magnetization of cosmic space is complex and various processes are likely to contribute to it, though to a different extent in different environments. One of the strengths of the model we describe below is that it generates relatively strong macroscopic fields throughout cosmic space, while having a simple description based on well understood physical processes.

[1] these results appeared after the first submission of this paper

The remainder of this paper is organized as follows: In Section 2 we introduce the resistive mechanism for the generation of magnetic field. In Section 3 we describe a cosmological simulation to determine some of the parameters describing the intergalactic medium that are required to quantify the generation of magnetic field. In Sections 4 and 5 we discuss the generation of magnetic field around individual galaxies using a numerical and slightly simplified analytical solutions, respectively. The solution is extended to the case of the intergalactic space in 6. Finally, we briefly summarize the main findings of this paper in 7.

In the following we use SI units and, unless explicitly stated, lengths are expressed in physical units, not comoving units.

2. RESISTIVE MECHANISM

Though, as discussed in the previous section, CR propagation in intergalactic space is unaffected by Coulomb collision and magnetic fields deflections, CRs are not completely decoupled from intergalactic plasma. This is due to the small current, $\vec{j}_c$, carried by the CR flux, which is assumed mainly to consist of protons. In fact, to maintain quasi-neutrality the CR current must be balanced by a return current carried by the thermal plasma $\vec{j}_t$. While the CR are collisionless with very long mean free paths, the thermal particles, due to their low energy, have mean free paths shorter than scale lengths of interest here. For example, at redshift $z \simeq 10$, when the intergalactic plasma had a temperature $\sim$ 1K and density $\sim 10^{-4}$cm^{-3}, thermal electrons had a Coulomb mean free path of only $10^5\psi^{-1}$m where ψ is the fractional ionization. Consequently an electric field in the rest frame of the plasma (indicated by a $'$) is required to draw the return current, namely

$$\vec{E}' = \eta \vec{j}_t, \tag{1}$$

where η is the plasma resistivity. Since Coulomb collisions dominate over charge-neutral collisions the resistivity takes approximately the Spitzer value, $\eta = 65T^{-3/2}\log\Lambda\ \Omega$m, where T is the temperature of the ambient thermal plasma in K, and $\log\Lambda \simeq 20$ is the Coulomb logarithm. The Spitzer resistivity is independent of electron number density and consequently independent of the degree of ionization.

The electric field transfers energy from the CR flux to the thermal plasma through ohmic heating, described by the equation

$$\frac{3}{2} n k_B \frac{dT}{dt} = \eta j_c^2 \tag{2}$$

where k_B is the Boltzmann constant. Since the charge-neutron collision time is much smaller than the expansion time of the universe, in Eq. (2) n is the total number particles in the plasma, to include heating of neutral as well as ionized particles. As a result of ohmic heating the temperature of the initially cold thermal plasma is raised.

The electric field also opposes the current carried by the CRs. In particular, CRs escape the parent galaxy to a distance R only if their kinetic energy at source exceeds the potential at R, $\phi = \int_0^R |E|dR$. This can determine the minimum energy of CR reaching R, giving

$$p_{min} = \frac{e\phi(R)}{c}\left(1 + 2\frac{mc^2}{e\phi(R)}\right)^{1/2} \tag{3}$$

As will be seen in figure 3, the electric potential is not sufficient to limit the escape of mildly relativistic protons from the galaxy for the cases considered here, largely because we assume that gas within 100kpc of a galaxy is hot (see below), and therefore has a low resistivity which results in a low electric field even though the CR current is relatively large close to the galaxy.

In a uniform medium, the electric field drawing the return current $\vec{j}_t$ cannot have a curl and therefore there is no generation of magnetic field. If the medium is non-uniform on a given scale, the forward and return currents can become separated on that scale producing a current loop which in turn supports a magnetic field. However, the separation of forward and return currents, and the corresponding magnetic field, is opposed by inductive effects, and the actual growth of magnetic field must be determined by self-consistent solution of the Maxwell equations

$$\nabla \times \vec{B} = \mu_0(\vec{j}_c + \vec{j}_t), \tag{4}$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}. \tag{5}$$

The displacement current can be neglected because timescales are much longer than the light transit time and the system evolves through a series of quasi-neutral steady states. Using Ampère's law (4) to eliminate the thermal current we find that the electric field (1) in the frame in which the the plasma moves at velocity $\vec{v}$, is $\vec{E} = -\vec{v}\times\vec{B} + (\eta/\mu_0)\vec{\nabla}\times\vec{B} - \eta\vec{j}_c$. The curl of this electric field then produces growth of magnetic field according to Faraday's law[2]

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\times(\vec{v}\times\vec{B}) - \vec{\nabla}\times\left(\frac{\eta}{\mu_0}\vec{\nabla}\times\vec{B}\right) + \vec{\nabla}\times(\eta\vec{j}_c). \tag{6}$$

The first term on the right hand side transports the frozen-in field with the plasma and can stretch and amplify an already existing magnetic field. The second term represents resistive diffusion and can easily be verified to be insignificant for kpc distances and Gyr timescales. Crucially, in contrast, the final *resistive* term of the equation produces magnetic field in a previously unmagnetized plasma. The magnetic field grows wherever the resistivity varies perpendicularly to the CR current. A larger electric field is needed to draw the return current where the resistivity is higher, so the electric field has a curl and magnetic field grows. These equations are well known in laser-produced plasmas where the current is carried by energetic laser-produced electrons in place of Supernovae-produced CRs protons (Bell & Kingham 2003).

[2] Adiabatic losses due to cosmic expansion are negligible during the ~ 1 Gyr in which the resistive process is efficient.

Temperature inhomogeneities, resulting in variations in conductivity, are naturally present throughout intergalactic plasma due to the growth of cosmological structure. In addition, because the volume heat capacity is proportional to density, where ohmic heating is significant, inhomogeneous temperature enhancements will arise from density inhomogeneities. On the other hand, the CR current is expected to be approximately uniform because as discussed previously sections, CR are relatively undeflected by collisions or magnetic fields in the intergalactic medium. Thus the magnetic field may be generated by the resistive term at a rate

$$\dot{B} = |\vec{j}_c \times \vec{\nabla}\eta| \simeq \frac{j_c\eta}{L_T}, \tag{7}$$

where, $L_T \equiv T/|\nabla T|$, is the characteristic temperature scale.

It is clear from the above expression that the resistive process depends sensitively on the plasma temperature through η. In particular, it operates efficiently while the intergalactic medium is cold, and it effectively shuts down once reionization raises the intergalactic gas temperature above 10^4 K. For a universe that is reionized at redshift $z \geq 6$ (Ciardi & Ferrara 2005), the available time is of order a Gyr. Note that close to the star-forming galaxies the gas temperature is $\geq 10^4$K due to both photoheating from the ionizing flux escaping the galaxies and the ohmic heating. For the above choice of the reionization epoch, the typical size of HII regions at $z \simeq 10$ is about 100 kpc (or 1 comoving Mpc, Zahn et al. 2007).

In order to quantify the importance of the resistive process in the following we first use a numerical simulation of structure formation to compute the scale of the temperature variations in the intergalactic medium. We then estimate the generation of magnetic field around individual star-forming galaxies at the epoch of re-ionization, including self-consistently the effect of the induced electric fields on the escaping CR particles and ohmic heating. Finally, we estimate the distribution of magnetic fields produced in intergalactic space.

3. COSMOLOGICAL SIMULATION

We extract characteristic scale-length L_T and the characteristic range of values taken by L_T from a cosmological simulation of structure formation which includes hydrodynamics, the relevant thermodynamic processes for the diffuse baryonic gas, dark matter and gravity. The simulation does not include the cosmic ray effects discussed in this paper. The simulation uses a directionally un-split higher order Godunov's method for the hydrodynamics, a time centered modified symplectic scheme for the collisionless dark matter and we solve Poisson's equation with a second order accurate discretization (Miniati & Colella 2007a). Atomic cooling, with rates as given in Hui & Gnedin (1997), is included according to the algorithm proposed in (Miniati & Colella

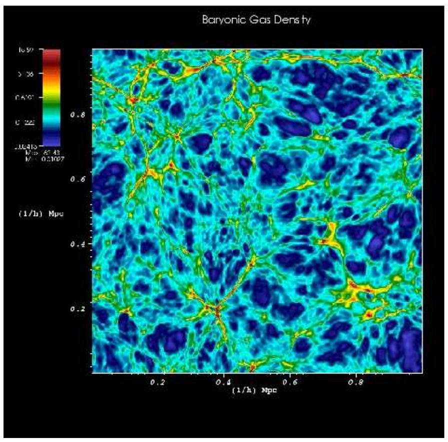

FIG. 1.— Baryonic gas density distribution.

2007b; Miniati 2010), although prior to reionization adiabatic expansion of the universe is the most relevant cooling process. We adopt a flat ΛCDM universe with the following parameters normalized to the critical value for closure: total mass density, $\Omega_m = 0.2792$, baryonic mass density, $\Omega_b = 0.0462$, vacuum energy density, $\Omega_\Lambda = 1 - \Omega_m = 0.7208$ (Komatsu et al. 2009). In addition, the normalized Hubble constant is $h \equiv H_0/100$ km s^{-1} Mpc^{-1} = 0.701, the spectral index of primordial perturbation, $n_s = 0.96$, and the rms linear density fluctuation within a sphere with a comoving radius of 8 h^{-1} Mpc, $\sigma_8 = 0.817$ (Komatsu et al. 2009). We generate the initial conditions with the grafic2 package (Bertschinger 2001). We use a computational box of comoving size $L = 1h^{-1}$ Mpc, discretized with 512^3 comoving computational cells, providing a nominal spatial resolution of $2h^{-1}$ comoving kpc for the field components, and 512^3 particles with mass $4.8 \times 10^2 h^{-1}$ M$_\odot$ for the collisionless dark matter component. At redshift $z = 6$ the box size in physical units is $\simeq 143\ h^{-1}$kpc and, likewise, the nominal spatial resolution is $\simeq 285\ h^{-1}$pc. Thus, structures with spatial scales between 1-10 kpc should be adequately resolved for our purposes.

Figure 1 shows the distribution of the baryonic gas density at $z \simeq 10$ on a two dimensional slice across the simulation box. One can recognize a few high density collapsed structures where gas is rapidly cooling. These are the sites where stars and galaxies form and CR are eventually produced. However, most of the gas ($\sim 97\%$ by mass) is still in the diffuse phase, with a density within a factor a few of the mean value. Figure 2 shows the occurrence of spatial scale-lengths in the range 1-10 kpc in the low density, low temperature gas which occupies most of the intergalactic space.

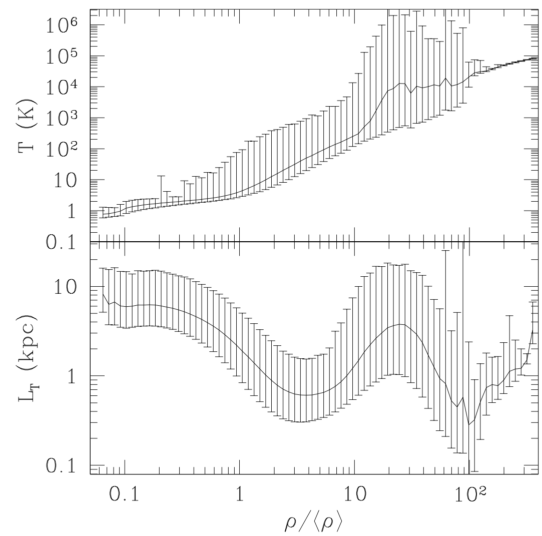

FIG. 2.— Temperature (top) and its characteristic length scale (bottom) as a function gas density in units of its average value. The vertical bars represent the asymmetric root-mean-squared fluctuations about the mean.

Note that the residual fraction of free electrons in the intergalactic medium after recombination keeps the gas temperature T locked to the CMB temperature, $T_{CMB} = 2.725(1+z)$ K, until redshift $1+z = 142(\Omega_b h^2/0.024)^{2/5} \simeq 140$ (Peebles 1993). After that the temperature of the diffuse intergalactic medium drops due to adiabatic expansion following the $\gamma-$law for a monoatomic gas with $\gamma = 5/3$.

4. SOLUTION AROUND INDIVIDUAL GALAXIES

The growth of magnetic field around an individual galaxy is described by Eq. (7). To solve this equation in the following we use the temperature scale-length derived from the simulation in the previous section as a reference value for L_T. In addition, we will determine the CR current produced by a galaxy of a given luminosity. The current determines the electric field which sets the minimum momentum of the escaping CRs, Eq. (3), from which the current itself depends. In addition, the electric field is effectively related nonlinearly to the current because the resistivity is affected by ohmic heating, Eq. (2). So all these equations need to be solved self-consistently.

The luminosity of a typical bright galaxy at redshift $z \geq 6$, is $L_* \simeq 5.2 \times 10^{21}\,\mathrm{W\,Hz^{-1}}$, corresponding to a star formation rate $\dot{M}_* = 6.5\,M_\odot\,\mathrm{yr}^{-1}$ (Bouwens et al. 2007). If we conservatively assume a Salpeter initial mass function, the energy released by SN explosions per unit mass of formed stars is, $E_{SN} \simeq 5.4 \times 10^{42}\,\mathrm{J}\,M_\odot^{-1}$. A fraction, $\epsilon_c \simeq 30\%$, of this energy is typically converted into CR particles, implying a CR-luminosity, $L_c \simeq 3.2 \times 10^{35}\,\mathrm{W}\,(\epsilon_c/0.3)\,(L/L_*)$, for a galaxy of luminosity L. The corresponding CR energy flux at a distance R from the galaxy is $Q_c \simeq 2.7 \times 10^{-5}\,(\epsilon_c/0.3)\,(L/L_*)\,(R/\mathrm{kpc})^{-2}\,\mathrm{Wm}^{-2}$, where we have idealized the galaxy as an isotropic point source of CR. If the CRs are collimated within a solid angle Ω_c then the CR current intensity is higher by a factor $4\pi/\Omega_c$,

although this does not change the qualitative picture. The CR momentum distribution can be expected to be $p^{-2.3}$ as typically observed for CR production by shocks in the Galaxy. With this power-law, most of the energy resides in mildly relativistic protons. The electric current is predominantly carried by the lowest momentum CR. In the following analysis, the electric field is allowed to inhibit CR propagation, although we find that inhibition is negligible for our conditions. If only CR with momentum greater than p_{min} reach a radius R, the current carried by CR at that radius is approximately given by $j_c = 5 \times 10^{-10} Q_c (p_{min}/m_p c)^{-0.3}/(p_{min}/m_p c + 1)$ Amp m^{-2} where m_p is the proton mass. Taking the efficiency of CR production to be fixed at $\epsilon_c = 0.3$

$$j_c \simeq 5.3 \times 10^{-14} \left(\frac{L}{L_*}\right) \left(\frac{R}{\mathrm{kpc}}\right)^{-2} \left(\frac{p_{min}}{m_p c}\right)^{-0.3} \left(1 + \frac{p_{min}}{m_p c}\right)^{-1} \mathrm{Amp\ m}^{-2} \quad (8)$$

This CR current must be balanced by an equal but opposite return current drawn by an electric field $E = \eta j_c$, giving

$$E \simeq 6.9 \times 10^{-11} \left(\frac{L}{L_*}\right) \left(\frac{R}{\mathrm{kpc}}\right)^{-2} \left(\frac{p_{min}}{m_p c}\right)^{-0.3} \left(1 + \frac{p_{min}}{m_p c}\right)^{-1} \left(\frac{T}{\mathrm{K}}\right)^{-3/2} \mathrm{V\ m}^{-1}. \quad (9)$$

So we can now solve numerically the coupled system of equations (2), (3), (8), (9), to determine the propagation of CR through the intergalactic medium surrounding a star forming galaxy, the associated electric field and the ensuing generation of magnetic field. Our 'standard' calculation is as follows. We treat the galaxy as a spherically symmetric source of CR which is constant in time. We set an inner radial boundary to the computational grid at $r_{min} = 10$kpc which corresponds to the notional radius of the galaxy. We assume that all CR produced by the galaxy escape through this boundary for the reasons given in Section 1. As will become clear below, changing r_{min} has very little effect on the results for the intergalactic medium on Mpc scales. The CR flux is specified at the inner boundary as a power law ($\propto p^{-2.3}$) with a minimum momentum of $0.1 m_p c$ which corresponds to a proton velocity a few times the shock velocity of an expanding young supernova remnant. We set the initial intergalactic temperature to 2×10^4K within a radius of 100kpc to represent heating due to ionization by the galaxy. Outside this radius we set the initial temperature to 1 K, with the temperature changing between the two regions over a distance of 10kpc. We set the intergalactic density to 10^{-4}cm^{-3}.

4.1. *CR propagation and magnetic field generation*

Figure 3a shows the results for our standard calculation, as defined above, for CR propagation and plasma heating as a function of radius for a galaxy with typical luminosity $L = L_*$ at time $t = 1$ Gyr. The horizontal scale is logarithmic and stretches from the edge of the galaxy at 10kpc to a distance of 10Mpc which is characteristic of the distance between bright galaxies at

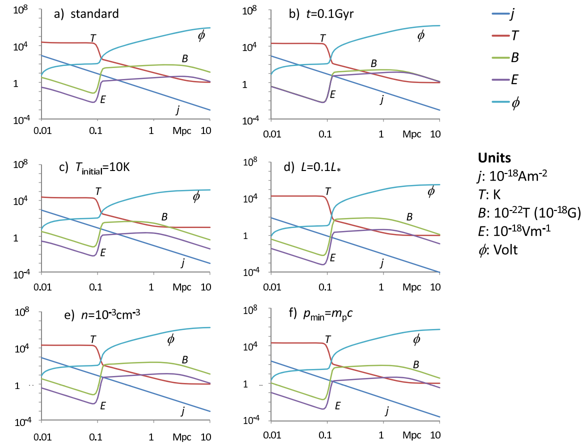

FIG. 3.— Spatial profiles at radii between 10kpc and 10Mpc. a) standard calculation, b)-f) as for the standard calculation with one parameter changed as indicated. The units are CR current density j in 10^{-18}Am^{-2}, temperature T in degrees K, magnetic field B in 10^{-22}T (10^{-18}G), electric field E in 10^{-18} Vm^{-1}, electric potential ϕ in Volt.

this epoch. Ohmic heating is effective out to a radius of ~ 3Mpc where the electric and magnetic fields reach their maximum values. The magnetic field is less within this radius because ohmic heating reduces the resistivity and the growth of magnetic field. Within 100kpc the magnetic field is much smaller because the temperature is initialized to a much larger value to represent ionization by the galaxy. The magnetic field is largest at ~ 3Mpc, but the maximum is broad, and fields above 10^{-17}G extend from 100kpc to 10Mpc. Figure 3b displays the profiles at the earlier time of 0.1Gyr for the same parameters. The fields are slightly reduced but still reach 2.5×10^{-17}G, once again with a broad maximum. This shows that most of the field generation occurs quickly before ohmic heating reduces the resistivity. Fields in the range $10^{-17} - 10^{-16}$G are produced even if suitable conditions for growth apply for much less than 1Gyr.

We take figure 3a as the standard calculation and then vary individual parameters in figures 3c-3f. Fields of a similar magnitude are produced if the initial temperature is raised to 10K (figure 3c), the CR luminosity of the galaxy is reduced tenfold (figure 3d), the density is increased to 10^{-3}cm^{-3} (figure 3e), or the minimum CR energy is increased to $p_{min} = \mathrm{m_p c}$ (figure 3f). Clearly the production of fields in the range $10^{-17} - 10^{-16}$G is robust. The results indicate that fields as large as $\sim 10^{-20}$Tesla (10^{-16}Gauss) are produced in a few to several $\sim$Mpc^3 volume surrounding galaxies if the temperature or density vary on kpc scales.

The plots of the electric potential ϕ in figure 3 show that the electric field does not inhibit the escape of CR from the galaxy.

5. ANALYTIC SOLUTION FOR A FIXED CURRENT

For the cases considered above, the electric potential does not inhibit CR transport. If the galaxy can be assumed to produce CR at a constant rate, the CR current is constant at any point outside the galaxy. The evolution of the temperature and magnetic field at that point is then determined by the equations

$$\frac{dB}{dt} = \frac{\eta j_c}{L_T} \quad ; \quad \frac{dT}{dt} = \frac{2\eta j_c^2}{3nk_B} \tag{10}$$

The solution is

$$B = \frac{3}{2} B_1 \frac{j_1}{j_c} \left(\left(1 + \frac{5}{3} \frac{j_c^2}{j_1^2} \right)^{2/5} - 1 \right) \tag{11}$$

where T_1 is the initial temperature in Kelvin, $B_1 = (\eta_1 n k_B T_1 t / L_T^2)^{1/2}$, $j_1 = (n k_B T_1 / \eta_1 t)^{1/2}$, and η_1 is the resistivity at temperature T_1. The magnetic field is largest when $j_c = 5.15 j_1$. When j_c exceeds $5.15 j_1$, ohmic heating increases the temperature, and reduces the resistivity, which in turn reduces the growth of magnetic field. Ohmic heating is marginally important when $j_c = 5.15 j_1$. At this CR current the magnetic field achieves a maximum value, $B_{\max} = 1.046 B_1$. Expressed in more meaningful terms, after a time t in Gyr, the maximum field is

$$B_{\max} = 8.2 \times 10^{-17} \left(\frac{L_T}{\mathrm{kpc}} \right)^{-1} \left(\frac{T_1}{\mathrm{K}} \right)^{-1/4} \tag{12}$$

$$\times \left(\frac{n}{10^{-4}\mathrm{cm}^{-3}} \right)^{1/2} \left(\frac{t}{\mathrm{Gyr}} \right)^{1/2} \mathrm{G}.$$

The maximum field occurs where the CR current ($j_c = 5.15 j_1$) is

$$j_{\max} = 3 \times 10^{-20} \left(\frac{n}{10^{-4}\mathrm{cm}^{-3}} \right)^{1/2} \left(\frac{T_1}{\mathrm{K}} \right)^{5/4} \tag{13}$$

$$\times \left(\frac{t}{\mathrm{Gyr}} \right)^{-1/2} \mathrm{Am}^{-2} \, ,$$

and the maximum field occurs at a distance $R_{\max}$ from a galaxy with luminosity L, where

$$R_{\max} = 1.9 \left(\frac{n}{10^{-4}\mathrm{cm}^{-3}} \right)^{-1/4} \left(\frac{T_1}{\mathrm{K}} \right)^{-5/8} \left(\frac{L}{L_*} \right)^{1/2} \tag{14}$$

$$\times \left(\frac{p_{\min}}{0.1 m_p c} \right)^{-0.15} \left(1 + \frac{p_{\min}}{0.1 m_p c} \right)^{-1/2} \left(\frac{t}{\mathrm{Gyr}} \right)^{1/4} \mathrm{Mpc}$$

in a medium with a proton density n. With the proviso that $R_{\max}$ lies in a realistic range, $B_{\max}$ is independent of the emissivity of the CR source, the CR momentum $p_{\min}$ and the fraction of CR escaping the galaxy. $B_{\max}$ is proportional to the inverse of the temperature scale-length, but all other dependences are relatively weak. The weak dependence on the initial temperature implies that significant magnetic field is generated even if the initial temperature is greater than 1K. Hence, the characteristic magnetic field is robustly of the order of 10^{-17} to 10^{-16}G when the effect of Ohmic heating is included in the calculation. The maximum magnetic fields and their spatial locations in figure 3 obey these equations. The weak dependencies on various parameters results in the broad extent of the maxima in figure 3.

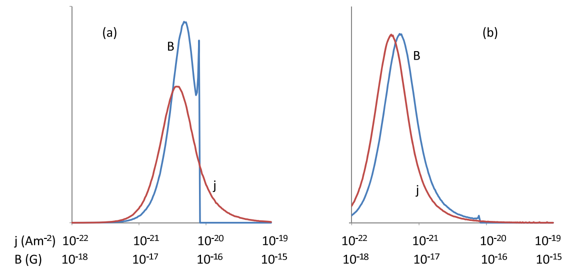

FIG. 4.— a) Distribution functions of current and magnetic field for galaxies randomly distributed in space according to the Schechter function. Apart from the luminosity the Monte Carlo calculation adopts the standard parameters used in figure 3a. b) distribution functions when the CR luminosity of all galaxies is reduced tenfold.

6. SOLUTION FOR THE INTERGALACTIC MEDIUM

The number density of star forming galaxies at redshift $z \geq 6$, with luminosity, L, and per luminosity interval, dL/L_*, is well described by a Schechter function

$$\Phi(L) = \Phi_* \left(\frac{L}{L_*} \right)^{-\alpha} \mathrm{e}^{-L/L_*} \tag{15}$$

with the following parameters: $L_* \simeq 5.2 \times 10^{28}\,\mathrm{erg\,s^{-1}\,Hz^{-1}}$, $\Phi_* \simeq 10^{-3}\mathrm{Mpc}^{-3}$, $\alpha \simeq 1.77$ (Bouwens et al. 2007; Oesch et al. 2009; Bouwens et al. 2010). L_* is the typical luminosity of a bright galaxy and Φ_* roughly corresponds to their number density. α is the slope of the distribution at the faint luminosity end.

The electric current at any given point in intergalactic space is contributed by galaxies within the current horizon, R_{jh}. As long as the diffusion coefficient remains much larger than Bohm's value, as observed in the much more turbulent interstellar medium of the Galaxy (Dröge & Kartavykh 2009), even for $B \sim 10^{-16}$G, R_{jh} is of order a few tens of Mpc, i.e. larger than the average distance between bright galaxies. Magnetic field generation is thus expected to be dominated by the nearest luminous galaxy. This is the case even if the currents are beamed with an opening angle $\theta \sim 0.5$ rad. In this case, the number of CR current sources visible from any given point is,

$$N_c = \Phi_* \Gamma(2-\alpha) R_{jh}^3 (\theta^2/4\pi) \sim 1, \tag{16}$$

for $R_{jh} \geq$ a few $\times$ 10 Mpc. Therefore, each point in space is exposed to the CR current from about one galaxy. Note that because the faint-end slope of the above Schechter's function is steep, i.e. $\alpha \lesssim 2$, the CR output per luminosity log-interval, $\epsilon_c L_* (L/L_*)^2 \Phi(L) \simeq \epsilon_c L_* (L/L_*)^{2-\alpha} \Phi_*$, is approximately constant. However, the average distance between faint galaxies of luminosity L is

$$\langle d_L \rangle = [L\Phi(L)]^{-1/3} \propto L^{(\alpha-1)/3}, \tag{17}$$

so that their CR current at this distance scales as

$$j_c(L, d_L) \propto \epsilon_c L / \langle d_L \rangle^2 \propto L^{1/2}, \tag{18}$$

i.e. fainter galaxies are slightly less efficient at magnetizing their surroundings.

We now make a more quantitative estimate through a Monte-Carlo simulation in which galaxies are distributed randomly in space according to the Schechter function as

given in equation (15). The currents from each galaxy are added vectorily and the calculation repeated many times to build-up a distribution function for the CR currents found at any random point in space. The magnetic field is then calculated using equation 11. Figure 4a gives the distribution functions for the current and the magnetic field for the standard parameters assumed in figure 3a. The distribution functions are defined as the number per logarithmic interval in j or B. The magnetic field calculation assumes that the initial temperature is 1K everywhere. It neglects heating during ionization, which was included in figure 3 within a radius of 100kpc, but this neglect has little effect on the distribution function, firstly because the ionized volume is relatively small compared with the characteristic distance of 10Mpc between luminous galaxies, and secondly because, even starting from a low temperature, ohmic heating reduces the resistivity, and therefore the magnetic field, in regions close to galaxies. For fixed parameters such as the temperature scale-length L_T and the plasma density n, the magnetic field cannot exceed a maximum value as given in equation 12. This produces an abrupt cut-off to the distribution function. The spike in the distribution function at the cut-off in figure 4a reflects the broad spatial extent of the maxima in figure 3a. The magnetic field is close to the maximum value over a wide range of distances from individual galaxies. In reality, as shown in figure 2, the temperature scale-length L_T takes a range of local values, and this will smear the cut-off. The effect of decreasing (increasing) the temperature scale-length L_T by a factor λ would be to move the distribution function for B a corresponding factor λ to the right (left) in figure 4a, while leaving the distribution function for j unchanged.

In figure 3 it can be seen that the value of the maximum magnetic field is insensitive to changes in various parameters. However the position of the maximum moves in radius. For example, the maximum magnetic field occurs at 1Mpc when the CR luminosity of all galaxies is reduced by a factor ten (see figure 3d where $L = 0.1L_*$). The effect of this on the distribution function for B can be seen in figure 4b. When the luminosity is reduced, there are still regions of space in which the magnetic field reaches the maximum value of 8×10^{-17}G, but the field is characteristically 10^{-17}G throughout most of the volume between galaxies. Similarly, the effect on the distribution function of changing other parameters can be deduced from figure 3 in conjunction with equation 12. Equation 12 gives a good estimate of the maximum magnetic field, while figure 3 indicates the volume of space that is filled by fields close to the maximum value.

7. SUMMARY

In conclusion, we have shown that cosmic rays produced by supernovae at the epoch of reionization when the first stars and galaxies form can be expected to have a substantial impact on the intergalactic medium out to distances of a several Mpc from the galaxy. Through the return electric current carried by the thermal plasma, the medium is heated ohmically and magnetic field is generated in the range 10^{-17} to 10^{-16}Gauss. Because of self-compensation through ohmic heating, the maximum magnetic fields are relatively insensitive to parameters such as the galaxy luminosity, the efficiency of CR production, and the ambient intergalactic temperature and density. The magnitude of the magnetic field is however sensitive to the scale-length L_T of temperature variations in the intergalactic medium. Cosmological simulations support an assumption of scale-lengths in the range 1-10kpc. Self-consistent cosmological simulations including cosmic ray effects are a necessary next step in developing this theory, but our argument extends the possibility that resistive magnetic field generation, driven by cosmic ray streaming, may generate seed magnetic fields which might subsequently be turbulently amplified to form the intergalactic magnetic field at the present epoch.

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